Nuclear Materials and Energy 000 (2016) 1–5

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Influence of friction stir welding conditions on joinability of oxide dispersion strengthened steel / F82H ferritic/martensitic steel joint

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Friction stir welding
Reduced activation metallic materials
Dissimilar joint
Backside plate
Joinability

ABSTRACT

As one of the joining methods for the reduced activation materials to realize the fusion reactors with high efficiency in the future, friction stir welding (FSW) is selected for fabricating the dissimilar butt joint between oxide-dispersion strengthened (ODS) alloy and F82H, and the effect of FSW conditions on joinability of this dissimilar joint was examined. The sound dissimilar joint can be produced under the condition that ODS plate is set on the advancing side and the FSW tool is plunged into F82H. As for the mild steel backside plate, the sound joint can be fabricated in the case of 150 rpm rotational speed and 50 mm/min traveling speed. On the other hand, by employing the silicon nitride backside plate, the total heat input should be decreased to obtain the sound joint, where the traveling speed is 100 or 150 mm/min and rotational speed is 150 rpm. In addition, the finite element heat conduction analyses indicate that the influence of traveling speed on the joinability with the mild steel backside plate seems to be smaller than that with the silicon nitride plate and the allowable range of the appropriate traveling speed for the joint becomes to be wider by employing the silicon nitride backside plate.

1. Introduction

As a result of research & development efforts on the reduced activation metallic materials, a well perceived reduced activation ferritic/martensitic steel F82H has been developed as for the first candidate structural materials for blanket module of fusion reactors [1–3]. In addition, by utilizing the powder technologies, ODS (oxide dispersion strengthened) ferritic steel has been developed and it is considered to be one of the most candidates for cladding materials of next-generation fission reactors [4–6]. In order to increase the flexible design margin and the economic efficiency in the advanced reactors, the joining method between the reduced activation materials and the other metallic materials has to be required. Although various fusion welding methods have been studied for joining F82H [1–3,7–10], these methods are inadequate for ODS alloys since the degradation in the performance of ODS alloys is occurred due to the agglomeration of nano-sized oxide particles in ODS alloys [5,6,11].

Recently, as one of the solid state joining methods, friction stir welding (FSW) has been widely examined for joining not only aluminum alloys [12,13] but also high strength steels [14], and its advantages to join F82H or ODS steels have been reported in comparison with the other joining methods [5,6,15]. However, there have been a few reports as for the dissimilar joint between F82H or ODS steels and other metallic materials [15–17] and the studies on FSW conditions for the dissimilar joint between ODS and F82H steels have not be conducted except for our preliminary report [16]. Where, the effects of the position of steels and plunged tool on joinability has been studied through the dissimilar friction stir butt joint between 15Cr-ODS and F82H steel plates. However, the influences of general other parameters in FSW such as compressive load, rotational speed and traveling speed have not been discussed. So, in this research, the effect of FSW conditions on the joinability of the dissimilar butt joint between 12Cr-ODS and F82H steel plates was examined. In addition, the mild steel plate is generally employed as the backside plate in FSW in order to en-

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http://dx.doi.org/10.1016/j.nme.2016.09.018

Table 1
Chemical composition of 12Cr-ODS and F82H used (unit: wt.%).

	Fe	C	Si	Mn	Ni	Cr	Mo	W	Ta	V	Ti	Y_2O_3
12Cr-ODS	Bal.	0.035	–	–	–	11.85	–	1.9	–	–	0.29	0.23
F82H	Bal.	0.097	0.1	0.44	< 0.002	7.81	< 0.002	1.86	0.058	0.2	–	–

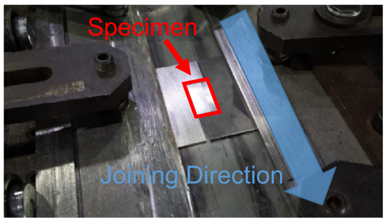

Fig. 1. Photo of specimen setup for ODS/F82H dissimilar friction stir butt joint.

Table 2
FSW conditions studied.

Backside plate			
Mild steel	Compressive load	(ton)	1.8–2.0
	Rotational speed	(rpm)	150–200
	Traveling speed	(mm/min)	50
Silicon nitride	Compressive load	(ton)	1.8
	Rotational speed	(rpm)	100–150
	Traveling speed	(mm/min)	50–200

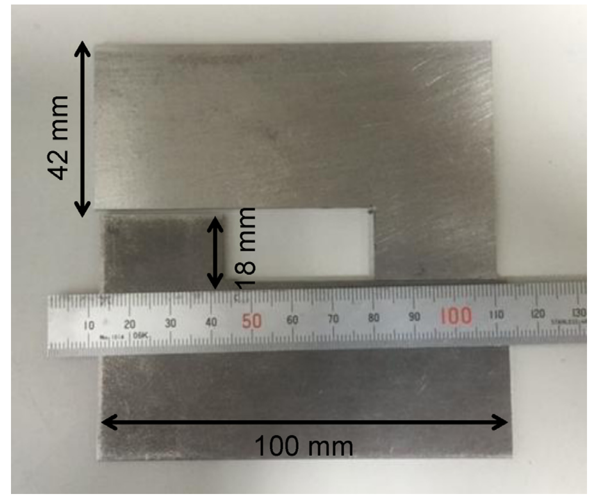

Fig. 2. Photo of special jig for ODS/F82H dissimilar friction stir butt joint.

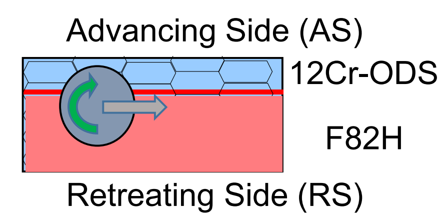

Fig. 3. Schematic illustration of ODS/F82H dissimilar friction stir butt welding.

hance the heat transfer from the specimen backside and to prevent its melting. However, in our preliminary research using the mild steel as the backside plate, there was as risk that the dissimilar joint was partially joined with the backside plate. Then, as one of the parameters in FSW conditions, the silicon nitride was selected as one of the backside plates in order to prevent the risk of joint between the dissimilar joint and the backside plate.

2. Experimental procedure

The materials used in this study were 12Cr-ODS ferritic steel and F82H ferritic/martensitic steel. The chemical compositions of these two steels are shown in Table 1. ODS was produced by mechanical alloying, where the Fe-12Cr powder was mixed with the Y_2O_3 powder by a high-energy attritor under an argon atmosphere. The resultant powder was subsequently consolidated by hot extrusion and forging at 1150 °C, then annealed at 1200 °C for 1 h. On the other hand, F82H steel was normalized at 1040 °C for 0.5 h and tempered at 740 °C for 1.5 h. ODS and F82H plates were cut into the specimens with the dimensions of 1.5 mm thickness, 40 mm length and 6 and 14 mm width, respectively.

As for FSW, a load-controlled FSW machine was employed. A tungsten carbide (W-C) based stir tool was used, where shoulder diameter, probe diameter and pin length were 12, 4 and 1 mm, respectively. Fig. 1 shows the photo of specimen setup. In order to prevent the separation of 12Cr-ODS and F82H plates, the outer edges of 12Cr-ODS and F82H plates were fixed by using the special jig (Fig. 2) during FSW. According to our preliminary study for the dissimilar friction stir butt joint between 15Cr-ODS and F82H plates [16], ODS plate was set on the advancing side and the FSW tool was plunged into the F82H plate, where the tool rotates clockwise as shown in Fig. 3. The tool tilt-angle was set as 3°. The tool probe was slightly shifted toward F82H plate and did not penetrate into the side of ODS plate. Then, as the parameters in FSW conditions, compressive load, rotational speed, traveling speed and type of backside plate were varied as shown in Table 2.

As shown in Table 2, the basic joinability of ODS/F82H joint was examined by using the mild steel as the backside plate. Metallurgical inspections were performed on a cross-section of the joint with an optical microscope after polishing and etching with 10 ml HCL + 5 ml HNO_3 + 85 ml ethanol solution. In addition, the Vickers micro-hardness tests were conducted on the same cross section where test temperature, indentation load and interval between measurement points were room temperature, 1.961 N and 0.3 mm, respectively.

3. Experimental results

Fig. 4 shows the cross sectional views and Vickers micro-hardness distributions of ODS/F82H joint with the mild streel as the backside plate where the traveling speed was 50 mm/min. Although 2.0 ton compressive load was needed for the friction stir butt joint of 15Cr-ODS plates and for the dissimilar friction stir butt joint of 15Cr-ODS and F82H plates [16,17], the flat joints could be obtained by reducing the compressive load to be 1.8 ton. In the case of 2.0 ton compressive load, the joint was bended by the excessive load and was partially joined with the backside plate. Also, the hardness distributions of the 1.8 ton compressive load suggest that the hardness in the stir zone was almost homogeneous when the rotational speed was 200 rpm, while the hardness in the stir zone distributed along the plate thickness in the case of 150 rpm. Moreover, it was revealed that the dissimilar joint could not be obtained when the rotational speed was 100 rpm because the plates were not be heated due to the heat transfer to the

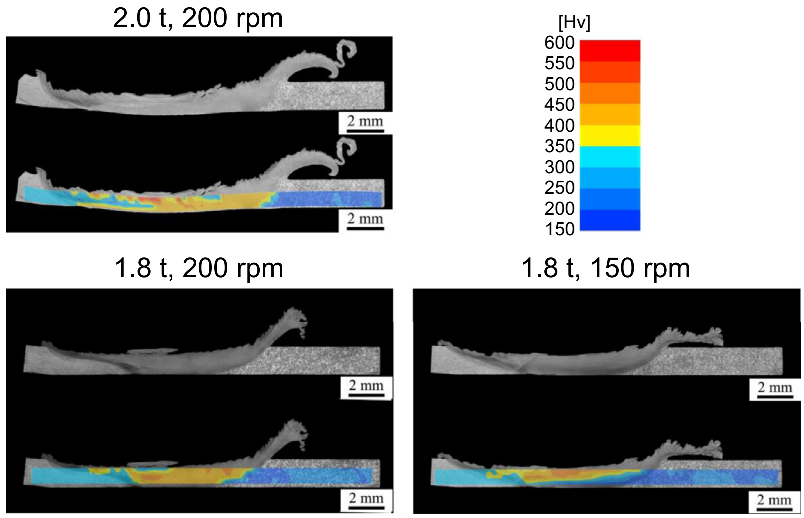

Fig. 4. Vickers micro-hardness distributions of ODS/F82H dissimilar friction stir butt joint with mild steel backside plate.

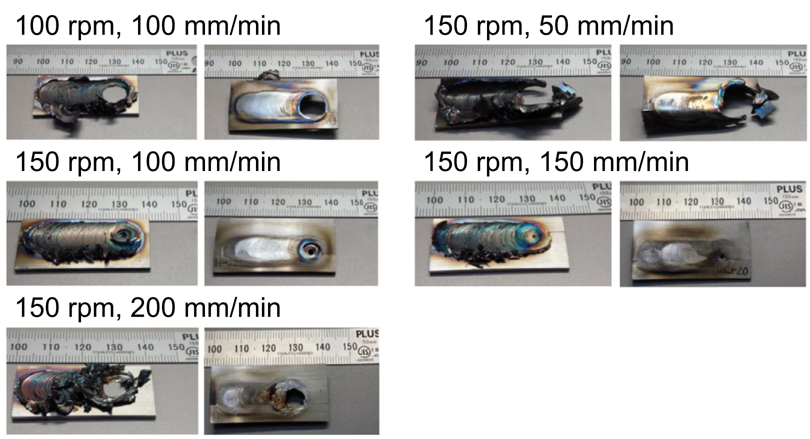

Fig. 5. Photos of ODS/F82H dissimilar friction stir butt joints with silicon nitride backside plate.

backside plates. Since FSW is one of the solid state joining methods and the smaller heat input is preferred, the 150 rpm seems to be an appropriate condition for the dissimilar joint between F82H and 12Cr-ODS when the mild steel is used as the backside plate.

On the other hand, by using a silicon nitride as the backside plate, the heat transfer from the specimen backside is prevented and the temperature of specimen is easy to increase in comparison with the case of mild steel backside plate. In addition, the total heat input is influenced by the rotational speed and the traveling speed. Concretely, the heat input Q (W) is reported to proportionally increase with increasing the rotational speed N (s^{-1}) and to decrease with increasing the traveling speed from the viewpoint of welding process according to the following equation which can be derived by the simple mathematical model [12].

$$Q = \frac{4}{3}\pi^2 \mu PNR^3 \qquad (1)$$

Where, μ, P and R are coefficient of friction, compressive load (N/m) and radius of shoulder (m), respectively.

Fig. 5 shows the surface and back appearances of the dissimilar joints between 12Cr-ODS and F82H joined by using the silicon nitride backside plate. From this figure, it is confirmed that the rotational speed for the silicon nitride backside plate should be decreased in comparison with that for the mild steel backside plate and the traveling speed for the silicon nitride would be faster than that for the mild steel. Also, these photos indicate that the sound dissimilar joint can be fabricated in the cases of 100 or 150 mm/min traveling speed and 150 rpm rotational speed by using the silicon nitride backside plate. Although the influence of rotational speed on the joinability can be predicted according to the empirical law shown in Eq. (1), the traveling speed effect have not be revealed quantitatively because the influence of heat transfer from the specimen backside on the joinability is unknown. So, the heat conduction analysis in FSW was conducted by using finite element method.

4. Method for numerical analysis

A finite element model for the heat conduction analysis is shown in Fig. 6. Both the small specimen and the special jig were modeled, and the specimen and the jig were assumed to be connected continuously because 12Cr-ODS and F82H plates were tightly fixed by the jig during FSW. The heat source was assumed to be a volumetric heat source according to our previous finite element heat conduction analysis for FSW, where 90 and 10% of the total heat input were set to be produced by shoulder and probe of the FSW tool, respectively [13]. The physical properties of 12Cr-ODS and F82H were set to be dependent on the temperature. Since the heat transfer from specimen backside to the silicon nitride plate is quite low, the coefficient of heat transfer was negligible and set as 0 W/(m^2 K) during the simulation. The total number of elements and nodes were 35,160 and 42,441, respectively.

Please cite this article as: H. Serizawa et al., Influence of friction stir welding conditions on joinability of oxide dispersion strengthened steel / F82H ferritic/martensitic steel joint, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.09.018

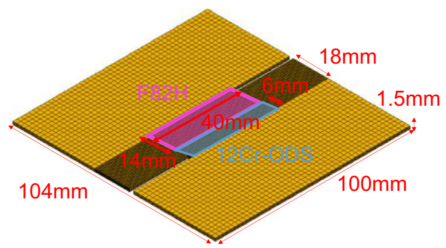

Fig. 6. Finite element model for heat conduction analysis of ODS/F82H dissimilar friction stir butt welding.

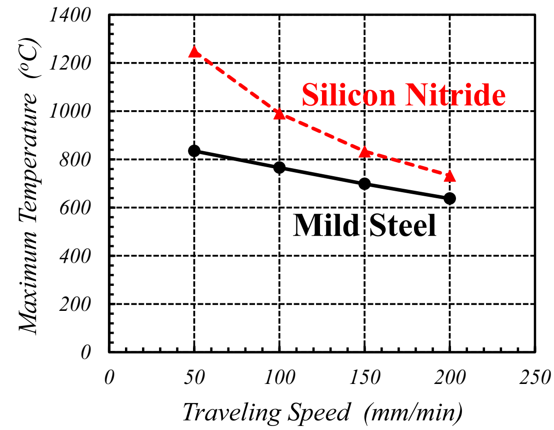

Fig. 7. Effect of traveling speed on maximum temperature in ODS/F82H friction stir butt welding.

5. Numerical analysis results

In the experiment, any temperature histories were not measured. From the hardness distributions shown in Fig. 4, it can be estimated that the center of joint seems to be the mixture of F82H and ODS in the case of 200 rpm rotational speed. On the other hand, in the case of 150 rpm rotational speed, the hardness distributed lamellary and only the surface of joint center would be the mixed phase. Although the microstructures in those joint should be analyzed precisely to identify the maximum temperature during FSW, this lamellar distribution indicates that the maximum temperature of joint produced in the case of 150 rpm would be lower than 840 °C which is Ac1 temperature of F82H because the maximum hardness measured was smaller than 500 Hv [15]. In addition, it was found that the surface appearance of joint fabricated in the case of 150 rpm & 50 mm/min with the mild steel backside plate is almost the same of joint in the case of 150 rpm & 150 mm/min with the silicon nitride backside plate. Because the temperature on the surface of joint center has the maximum value during FSW, the maximum temperature of joint in the case of 150 rpm & 150 mm/min with the silicon nitride backside plate is considered to be lower than 840 °C. So, the serial computations for the joint in the case of 150 rpm & 150 mm/min with the silicon nitride backside plate were conducted by varying the coefficient of friction in Eq. (1) in order to obtain the reasonable maximum temperature of joint and an appropriate value for the coefficient of friction was estimated to be 0.205. Although this value is smaller than the coefficient of kinetic friction for the steel on the steel in a dry condition generally reported [18], this value might be reasonable because the kinetic friction is largely affected by the surface conditions and the order of the value estimated agrees with that of the kinetic friction reported.

On the other hand, the coefficient of heat transfer from specimen backside with the mild steel is also unknown. From the hardness distributions shown in Fig. 4, the maximum temperature of joint in the case of 150 rpm & 50 mm/min with mild steel was considered to be lower than 840 °C. So, the serial computations for the joint in the case of were carried out by changing this coefficient of heat transfer in order to obtain the reasonable maximum temperature of joint with the mild steel backside plate. Then, the coefficient of heat transfer with the mild steel was estimated to be 3.2 times larger than that from the specimen surface to the air.

In order to examine the joinability of dissimilar joint between 12Cr-ODS and F82H in FSW, the maximum temperatures were calculated though the finite element heat conduction analyses by changing the traveling speed, where it was assumed that the coefficient of friction in Eq. (1) was 0.205 and the coefficient of heat transfer from the mild steel backside plate was 3.2 times larger than that from the surface to the air. The results are summarized in Fig. 7. The maximum temperature in the case of 50 mm/min with the silicon nitride estimated achieves more than 1200 °C, while that in the case of 200 mm/min with the silicon nitride computed is about 735 °C. These temperatures agree with the surface appearances shown in Fig. 5. In addition, Fig. 7 clearly indicates that the maximum temperature monotonically increases with decreasing the traveling speed and the rate of change in the case of silicon nitride backside plate is much faster than that in the case of mild steel plate. In other words, the effect of traveling speed on the joinability with the mild steel backside plate seems to be smaller than that with the silicon nitride plate. So, it can be concluded that, by employing the silicon nitride as the backside plate, the influence of the traveling speed on the joinability can be actualized and the allowable range of the appropriate traveling speed for the dissimilar butt joint between 12Cr-ODS and F82H joined by FSW becomes to be wider.

6. Conclusions

In order to reveal the influence of FSW conditions on the joinability of dissimilar joint between 12Cr-ODS and F82H, the experimental tests were conducted by varying compressive load, rotational speed, traveling speed and type of backside plate. In addition, the finite element heat conduction analyses were carried out in order to identify the influences of traveling speed and backside plate on the joinability. The conclusions are as follows,

1. The sound dissimilar butt joint can be fabricated under the condition that ODS plate is set on the advancing side and the FSW tool is plunged into the F82H where the tool rotates clockwise.
2. As for the mild steel backside plate, the sound dissimilar joint can be produced in the case of 150 rpm rotational speed and 50 mm/min traveling speed.
3. By employing the silicon nitride as backside plate, the total heat input should be decreased to fabricate the sound dissimilar joint, where traveling speed is 100 or 150 mm/min and rotational speed is 150 rpm.
4. The finite element analyses indicate that the influence of traveling speed on the joinability with the mild steel backside plate seems to be smaller than that with the silicon nitride plate.
5. The serial computations suggest that, by employing the silicon nitride as the backside plate, the allowable range of the appropriate traveling speed for the dissimilar joint becomes to be wider.

Acknowledgement

This work was performed with the support and under the auspices of the NIFS Collaboration Research program (NIFS11KOBF020).

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